



# Intelligent Systems for Power Management and Distribution

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# INTELLIGENT SYSTEMS FOR POWER MANAGEMENT AND DISTRIBUTION

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## ABSTRACT

The motivation behind an advanced technology program to develop intelligent power management and distribution (PMAD) systems is described. The program concentrates on developing digital control and distributed processing algorithms for PMAD components and systems to improve their size, weight, efficiency, and reliability. Specific areas of research in developing intelligent DC-DC converters and distributed switchgear are described. Results from recent development efforts are presented along with expected future benefits to the overall PMAD system performance.

## INTRODUCTION

As power electronics technology has advanced over the past decade, there has been increasing interest in replacing high maintenance mechanical and hydraulic systems in automobiles, aircraft, and aerospace vehicles with all electric systems. To achieve this goal the NASA Glenn Research Center is researching technologies that will enable more modular, reliable, and robust power management and distribution (PMAD) systems.

A PMAD system is defined as the power components necessary to "connect" electrical sources (generators, solar arrays, batteries) to the loads. In DC power distribution, the PMAD system is comprised of source regulators, storage charge/discharge regulators, voltage converters, and protective switchgear. Even the cable itself is part of the PMAD system.

To achieve this vision of reliable and robust PMAD systems, NASA Glenn is researching the benefits of using adaptive, robust, and distributed digital controllers in place of conventional analog controllers in devices such as DC-DC converters and protective switchgear.

Until recently the performance of available microprocessors and digital signal processors (DSPs) were too slow to be used in fast-acting, high frequency PMAD components. However, recent advances in the speed and size of these processors and periphery, such as analog-to-digital converters, has made their use now possible in all kinds of PMAD components and systems.

Just as the fuel efficiency and emission controls of the modern automobile would have been impossible without the advent of engine control computers, we expect that similar use of intelligent, digital control will have many benefits that will allow PMAD systems to achieve

- higher efficiency and lower weight
- better power quality and transient response
- higher fault tolerance and reliability, and
- lower integration costs.

It is really the last two bullets that will make or break electrical power systems in automotive and aerospace vehicles. While higher efficiency, lower mass, and better power quality can be achieved without digital control, there are many several reliability and integration problems that cannot be solved without digital control.

## POWER CONVERTERS

Many advantages of intelligent controls are expected to be found in the power converter function. These devices, typically DC-DC converters for spacecraft systems, are some of the most complicated and pervasive devices in the PMAD system. Very few loads can use the electrical distribution voltage directly, especially in high power spacecraft, so DC-DC converters are required to change voltage levels needed for the loads.

The most important characteristics of a DC-DC converter are its size, weight, efficiency, power quality, fault tolerance, and reliability. These characteristics are heavily inter-related. An improvement in one area may have additional benefits in another area. For example, a converter with high efficiency generates less heat, thereby reducing or eliminating any active or passive cooling. This results in a reduction in the size and weight of the converter.

Today's DC-DC converters rely solely on specialized analog circuits to perform control, regulation, and protective functions of the converter. However the linear, analog design limits their ability to adjust and adapt to the wide range of operating conditions. A digital controller, on the other hand, can easily make adjustments, thereby optimizing the control and operation of the DC-DC converter at all times.

## POWER EFFICIENCY

There are several methods for increasing the power efficiency of DC-DC converters using intelligent control. The first method involves non-linear control algorithms to improve the efficiency of a single DC-DC converter. The second method involves using digital controllers and a communication bus to coordinate the function of modular converters.

### Variable Switching Frequency

In many conventional DC-DC converters the switching frequency of the input bridge is fixed during the design to achieve a balance between overall efficiency and the size of passive components. As the switching frequency is increased, the size of the passive components is decreased (input capacitors, isolation transformer, and output capacitors) while the switching losses in the primary switch and rectifier diodes is increased. These trade-offs between increased losses and decreased size leads to a fixed frequency operation at one desired optimal point.

The addition of intelligent control can improve the "overall" efficiency of the converter by varying the switching frequency versus load.

By being able to lower the switching frequency of a converter at lower power, the switching losses can be reduced, thereby increasing the low-power efficiency of the converter. In experimental testing, a 1kW full-bridge DC-DC converter with a nominal frequency of 20kHz was switched at frequencies down to 5kHz at different power levels [1]. The data in Figure 1 shows a marked improvement in efficiency at lower frequencies, especially at low power levels.

It should be noted that the current and voltage ripple in the converter increased, as expected, when the switching frequency was reduced. However, the ripple magnitudes at low power were still well below that seen at full power loads.

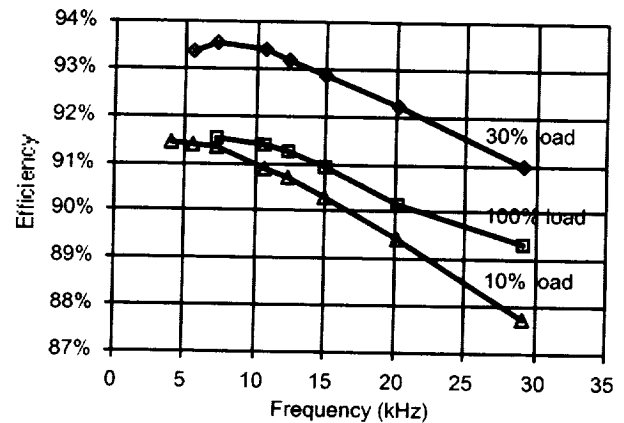


Figure 1 – Converter Efficiency vs. Switching Frequency

### Cooperation with Paralleled Units

In systems using on-line spare modules to increase reliability, intelligent control can again improve the overall system efficiency. These on-line spares used to meet N+1 redundancy requirements are excess modules above what the nominal power levels require. Therefore, if one of the modules fail, the excess module will allow continuous operation at rated power levels.

If the number of modules used is small (< 4) then the N+1 redundancy leads to converters operating at lower power levels with lower efficiency. For example, a 2kW load being fed by a converter made up of 1kW modules uses three converters to meet N+1 redundancy. If all converters are operational, then at 75% load (1.5kW) all three converters are operating at 500W each where efficiency is less than ideal. An intelligent controller would be able to coordinate the three paralleled converters so that at 75% load only two modules would be operational, resulting in higher overall efficiency.

## POWER QUALITY

Another area that can benefit from intelligent control is the size and power quality of the PMAD system. Power quality specifications for PMAD components and systems are written to ensure that voltage and current ripple in the system is kept to a minimum. These specifications have a profound impact on the design and sizing of passive components in DC-DC converters.

An approach to input filter reduction that has been used in custom DC-DC converters in the past is the technique of phase-staggering paralleled switch-mode power supplies (SMPS). This method coordinates the switching phases of the DC-DC converter input bridges so that the input current ripple from one converter is cancelled by other converters. By doing this, two benefits are accrued. First, the input current ripple magnitude is greatly reduced since the input currents cancel each other out when phase-staggered at  $360^\circ/N$  phase increments, where  $N$  is the number of converters operating in parallel or series.

Second, the input current ripple frequency is increased resulting in a ripple frequency that is  $f_s \cdot N$  where  $f_s$  is the baseline switching frequency. These two factors combine to significantly reduce the capacitive and inductive filtering which makes up a large part of all SMPS.

With current technologies, implementation of the phase-stagger between converters is coordinated by a single controller that accepts the timing signals from a "master" device and generates the staggered "slave" signals used to drive the other devices. This method was used in a recent investigation of phase-stagger benefits (Figure 2) and currently Vicor, Inc. [2] has developed a custom chip to provide phase-stagger functions for up to 12 units in parallel.

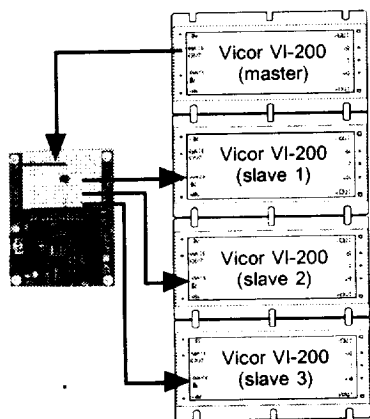


Figure 2 – Diagram of Vicor Phase Shift Test Setup

Using the test setup shown in Figure 2 it was found that phase-stagger techniques reduced the passive component sizes of the input filters by a remarkable 75-95% [3]. Test data is shown in Figures 3 and 4. As you can see, the unfiltered input current ripple has been greatly reduced from 6.75 A<sub>p-p</sub> to about 2 A<sub>p-p</sub> while the ripple frequency has been multiplied from 50 kHz to 200kHz. These improvements greatly reduce the amount of passive filtering needed to meet power quality and conducted electromagnetic interference (EMI) specifications.

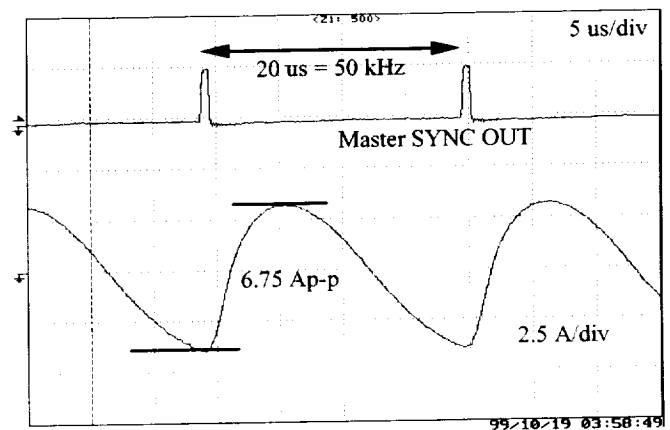


Figure 3 – Converters in-phase. Load = 3.1 A

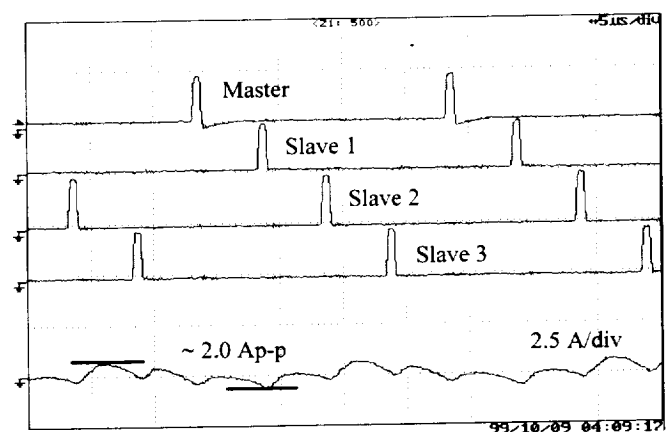


Figure 4 – Phase shifted converters. Load = 3.1 A

It is clear that the phase-stagger control is an ideal technology to improve PMAD system size and power quality. However, the dependence on a centralized controller results in a serious single-point failure that could bring down the entire converter. We can address the single-point failure problem and take advantage of the phase-stagger benefits by using an intelligent, digital controller in each converter.

There are two methods we are pursuing to allow this distributed cooperation with paralleled converters. Initially, we'll be investigating a high-speed data bus to synchronize and delay the switching phase of paralleled converters. For fixed frequency converters this adjustment does not need to be done on a cycle-by-cycle basis, so bandwidth requirements are not too critical. However, the communication protocol chosen may present latency problems that can interfere with the critical timing required for proper synchronization.

Ultimately, we want to develop an intelligent controller that can “listen” to the noise ripple on the system and adjust its switching phase to minimize it. This is expected to require very fast digital signal processors (DSPs) running fast Fourier transform (FFT) algorithms with closed loop control on minimizing harmonic amplitudes. If this technique is successfully developed, then each converter would have the means for independent operation, yet be able to negotiate with other devices to achieve minimized ripple currents and result in smaller, more compact DC-DC converters.

## COMPONENT HEALTH MONITORING

An intelligent controller can also monitor and track the health of some key components in the DC-DC converter. By monitoring the health of key components, impending failures may be predicted and allow for corrective actions to be taken before catastrophic failure. The corrective actions may include reducing load current to extend lifetime, activating on-line spares, or even replacing failing converters or devices on manned missions.

For DC-DC converters, the most likely source of failure occurs in the active devices—the input switches, the switch drive electronics, and the output rectifiers. These devices can fail instantaneously or can degrade gradually over time. Instantaneous failures cannot be predicted or, in many cases, prevented, so these failures will temporarily affect system performance. An intelligent controller does, however, have the ability to record sensor data during a failure offering important historical information to determine the cause of failure.

More importantly, an intelligent controller has the ability to “remember” past performance of the converter and can monitor trends in sensor data and control inputs over time that may signal the degradation of the active components. For example, we know that as MOSFETs degrade, their on resistance,  $R_{ds(on)}$ , increases resulting in higher conduction losses and higher operating temperatures that lead to further accelerated degradation. In a typical full-bridge DC-DC converter, as  $R_{ds(on)}$  increases, the pulse width needed to maintain regulation would also increase. By monitoring the load current vs. pulse width data over time, trends may be identified that portend the eventual degradation and failure of active switches.

Successful health monitoring requires confidence in the sensors used to measure key information. If sensor data suggest impending converter failure, it is important to be able to trust that a faulty sensor is not the cause for alarm. Intelligent systems have the added benefit of “sanity checking” sensor data in many components to rule-out sensor drift or failure. A good example would be the cross-checking of a DC-DC converter output current sensor against the input current sensor of a downstream device.

## SWITCHGEAR

Another area that we expect to benefit from intelligent control is in the application of remote power controllers (RPCs) in a PMAD system. An RPC is a semiconductor device that can provide load on/off control, soft-start/current limit, fault protection, and load shedding.

The functionality of the RPC is straightforward and can be implemented in analog control circuits. However, the unpredictable cable and load impedance characteristics can lead to stability problems with an analog controller. For example, coordinating the switch’s soft start algorithms with its protective function can lead to oscillations between the switch and the load. To combat these potential oscillations, many systems have in-rush current limit specifications levied upon the power converters. This forces the converter manufacturers to include series switch elements to limit the in-rush current, resulting in a system with one semiconductor switch followed by another semiconductor switch in series with the power flow. The result is redundant components, excess power losses, and additional failure modes.

An intelligent switch would be better suited to detect the amount of protection necessary, and would be able to coordinate with downstream devices to eliminate any instability. For example, an intelligent switch would “expect” the current to rise above trip levels when it is turned on into a load and could arbitrarily extend the time limit to prevent oscillations. Once at steady state, another control algorithm would take over shortening the time limit to respond to true faults quickly. This type of flexibility is difficult to achieve using analog control circuits.

## SOFT FAULT DETECTION

Intelligent switchgear could also provide advanced fault detection algorithms for hard-to-detect faults like continuous soft-faults and arcing faults. These faults, typically caused by failures in the wire insulation, cause low amplitude currents or intermittent sparking between hot and ground or hot and return. These faults do not draw large amounts of current and therefore go undetected by conventional protection devices. While the faults do not cause system disturbances, they pose a serious fire threat as “hot spots” develop that can ignite combustible materials. In fact, a recent report has concluded that arcing faults played major roles in two recent airline disasters, TWA flight 800 in 1996 and the Swissair III crash off Nova Scotia in 1998 [4].

Analog detectors can do a good job of detecting continuous soft faults. The common household ground fault circuit interrupter (GFCI) is a good example. This device simply detects a ground fault by sensing an

imbalance between line and neutral currents using a common core.

The continuous line to neutral fault is more difficult to detect in that there is no imbalance between line and neutral. The only way to detect this fault is to measure an imbalance at each end of the cable. This is where intelligent power systems can help. By using the data gathered from the distributed sensors included in each component, hot to return faults can be detected.

Unfortunately, intermittent arcing faults may escape all conventional analog detection methods due to their very high frequency content and short time duration. One possible detection method is to use high-speed signal analysis to detect the high frequency signature of an arcing fault in the system. Again, distributed digital signal processors will be able to perform this signal analysis and may even be able to coordinate their analysis results to determine an approximate location of the arcing fault. The biggest challenge to this method of arc fault detection is the ability to ignore electrical arcs produced normally by motors, relays, and manual switches. The NASA Glenn Research Center along with Howard University has begun a program to characterize arc faults in high voltage DC systems and to develop advanced algorithms to detect and locate the faults.

## **SYSTEM BENEFITS**

While the concepts presented so far could have positive impacts on almost all PMAD systems, the real benefits are to be found in large, distributed power systems such as the International Space Station and possible future manned missions to Mars. In these systems, not only will components have better performance and higher reliability, but the intelligent controllers will also provide unparalleled levels of flexibility and reconfiguration that are possible in manned systems.

Some of these "system benefits" have already been discussed in the sections above such as the coordination between switchgear and converters to ensure stability and help detect faults.

However, intelligent PMAD components are expected to have the greatest impact on the system design and integration costs associated with large, complex, distributed systems. Two of the goals we are currently working toward for intelligent PMAD systems is "Plug and Play Configuration" and active stability control.

## **PLUG AND PLAY**

The phrase "Plug and Play" is borrowed from the mid-90's marketing of easy-to-integrate personal computer hardware

and peripherals. This improvement in hardware integration came from the adoption of hardware identification and programming technologies. In essence, the previously complex process of determining the hardware configuration, manually setting the proper jumpers to work with your system, and knowing what software drivers to install was reworked so that the computer and hardware could do all the work. This is our goal for future PMAD systems and components.

Specifically, we are developing technologies that will allow switchgear to "sense" the source and the load that it is connected between so that key setpoints will be automatically set. To do this, we have to develop technologies that would allow an intelligent component to "know" what device was feeding power to it and what loads were connected to it at all times. Knowing this information and the basic characteristics of the devices attached to it, the component would be able to make independent decisions about how to best handle any anomalies that would occur. Parameters such as maximum current levels or load prioritization could be autonomously set without having an army of ground-based engineers determine if a new configuration would cause any system instabilities.

The implications to having this amount of flexibility coupled with modular system design are great. It could mean that the amount of spare components required for long duration manned missions could be greatly reduced. For example, a failed component in a critical system could be easily swapped-out with a similar component in a non-critical system if they had the ability to reprogram themselves based on their location.

## **ACTIVE STABILITY**

One of the key problems with integrating large, distributed electrical power systems is guaranteeing stable operation between active control loops operating in series. Some examples of possible unstable operation include large DC-DC converters feeding smaller DC-DC converters, each with their own control loops. Also, the problem described previously with active switchgear feeding DC-DC converters causing relaxation oscillators.

Another goal of the intelligent PMAD system is to greatly reduce integration time and cost by developing technologies that will guarantee stability at all times. These will probably include advanced detection algorithms that will look for signs of instability and actively adjust controller gains to return to stable operation. By being able to guarantee stable operation at all times the daunting job of system stability design and analysis is eliminated. This should greatly reduce the time and cost associated with integrating large, complex PMAD systems in the future.

## COMMUNICATIONS

Finally, a critical element in developing an intelligent PMAD system is the inter-device communication. Without communication, intelligent devices would be very limited in their ability to detect and isolate faults, verify sensor data, and cooperate with other devices to improve power quality and reliability. By developing a high bandwidth, intra-device communication medium, the promise of an intelligent PMAD system can be achieved.

There are several technologies that we are considering for intra-device communication. Power-line communication technology uses the power cables to transmit digital information. This technology is very attractive since the PMAD devices would not require extra cabling for communication. However, it may not support the high bandwidth required for some functions, and transmitting signals across transformer isolated converters and switches in the off state remain a challenge.

Dedicated, high-speed serial busses like IEEE-1394 (a.k.a. Firewire or iLink) would likely be very capable in meeting the bandwidth requirements. However, the technology also defines a transport protocol that may not be as sensitive to latency as would be required. Also, each device would require extra data ports and dedicated data cables would be necessary for this implementation.

The most attractive option is a wireless communication technology. This would have the benefit of being high bandwidth and wouldn't require any extra cabling. The biggest issue will probably be the acceptance of on-board wireless communication in a space environment that is accustomed to being very noise-free.

## CONCLUSIONS

It is clear that future improvements to power management and distribution (PMAD) systems will be found in the flexible and robust control of intelligent, digital systems. They will be able to improve the performance of individual components using non-linear control optimization, and will open up vast possibilities of improving coordination and autonomy at the system level.

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